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SPACE LAUNCH SYSTEM

Modeling and Hot Fire Test Validation of Space Launch System Thrust Vector Control Friction Effects

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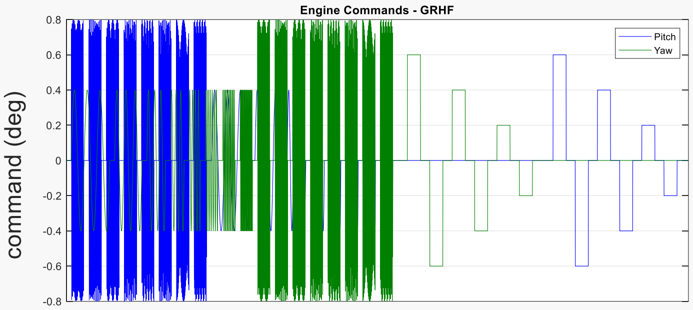
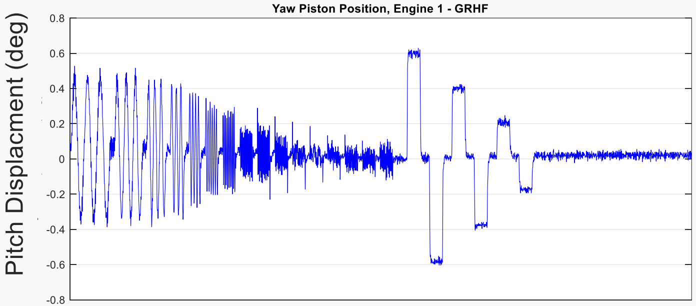
Overview

- Green Run Hot Fire (GRHF)
  - Test Design
  - Results
- TAOS – Two Actuator Operational Simulation
  - Introduction to TAOS
  - TAOS models and capabilities
- Modeling Friction
  - General Approach
  - Coulomb
  - Dahl
  - LuGre
    - Appended version
- Frictional Effects in TVC Performance
  - Test Data Analysis
  - Frequency domain characteristics
  - Time domain characteristics

Green Run Hot Fire - Test Design

- Measuring response
  - String potentiometers for engine position
  - Commanded current, sensed actuator position, sensed current at servovalve
- GRHF Test profile (displayed below)
  - Set of sine profiles in each axis
  - 3 step response amplitudes in each direction for each axis





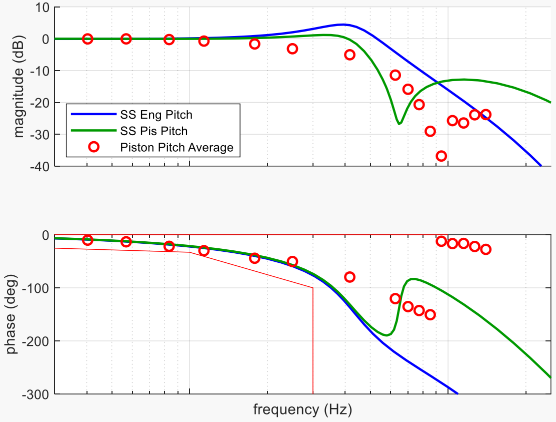
Green Run Hot Fire Video

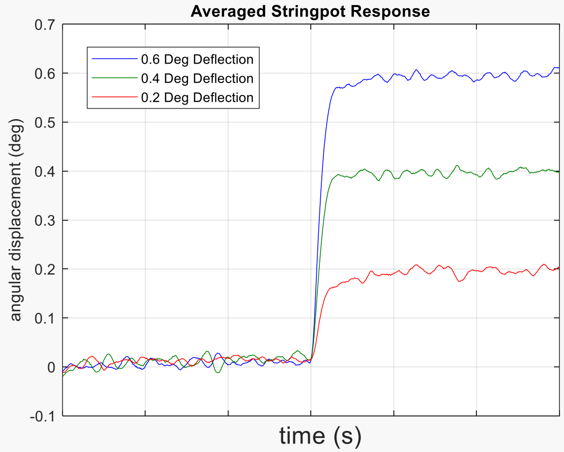
Pitch	Yaw
7-14 Hz @ 0.8°	0.40-6.25 Hz @ 0.4°
0.40-6.25 Hz @ 0.4°	7-14 Hz @ 0.8°
-	0.6°, 0.4°, 0.2° steps
0.6°, 0.4°, 0.2° steps	-

Green Run Hot Fire - Results

- Frequency Response
  - Hot fire shows clear resonance at 9.5 Hz
    - Represents an apparent shift from the ambient vectoring test result of 6.5 Hz
  - Gain degradation in low-mid frequencies
    - Indicative of friction effects
- Step Response
  - Step response shows hesitation not seen in prior modeling
  - Step shows a more damped response than in ambient test
- Importance of Proper TVC Modeling
  - Need to ensure stability of TVC and vehicle loop as they are coupled
  - Frictional effects may induce limit cycling in flight
  - Long standing question regarding the presence of gimbal friction in the RS25 gimbal (back to SSME)
- Overall
  - Nonlinear effects that were thought to be negligible needed to be modeled to match test data
  - Simplest possible model that could recreate these effects from test data was pursued (TAOS)

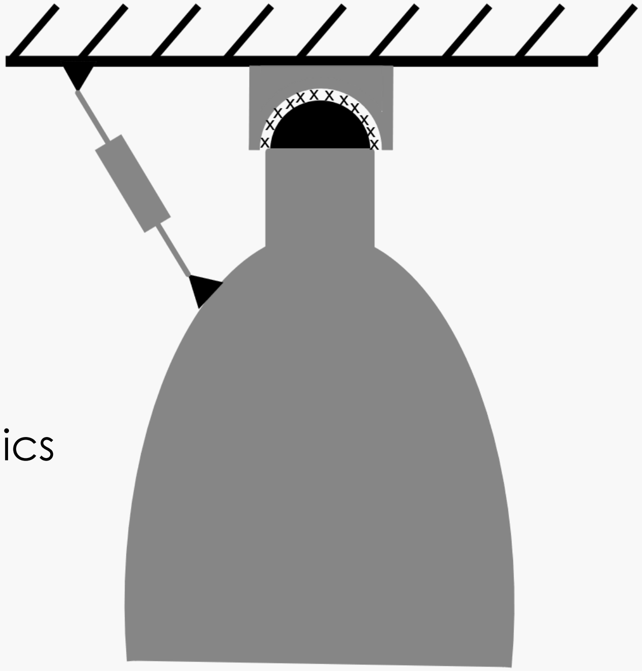
Command to Engine and Actuator Position Frequency Response





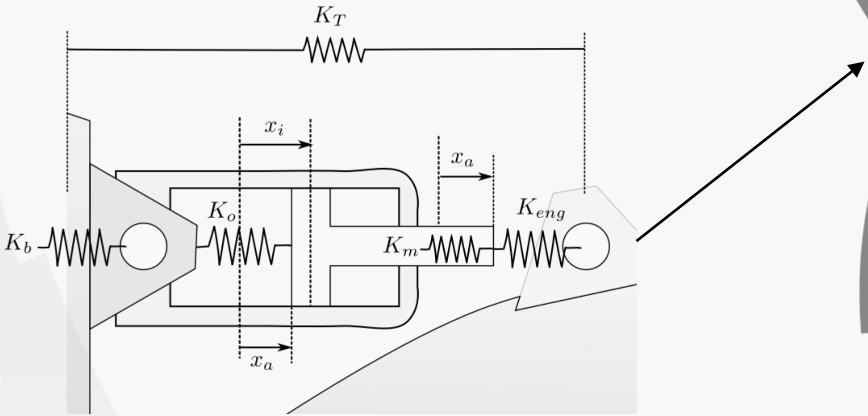
TAOS - Introduction

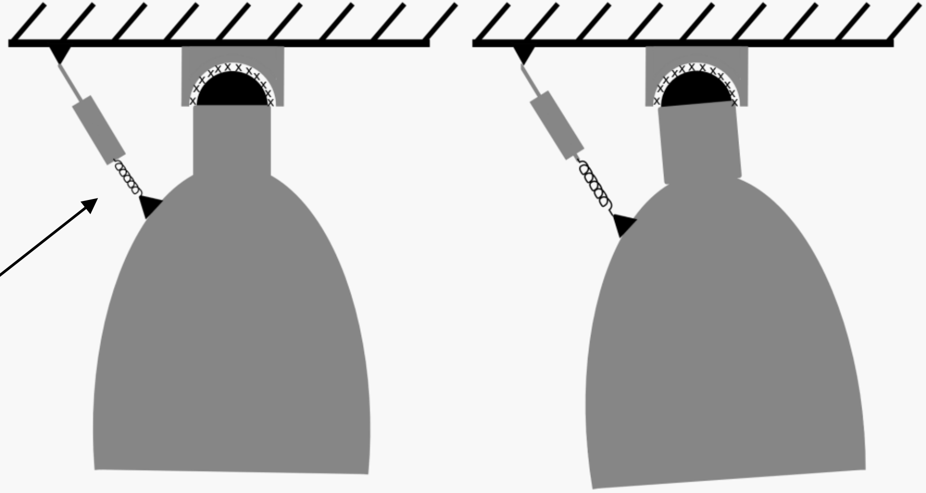
- TAOS seeks to take the traditional 1-DoF approach and incorporate the effects of movement into multiple DoF
- Effects include:
  - 6-DoF Engine Movement
    - Boltzmann-Hamel Equations
      - LaGrange's equations in rotating frame
      - Rotation and translation DoFs
  - Actuator
    - Kinematics of actuator attach
    - Internal dynamics of actuators
      - Heritage modeling method of actuator dynamics
    - Coupling effects of using two active actuators
    - Nonlinear controller effects
  - Friction on Gimbal Surface
    - Range of Models
    - Proper accounting of motion over a 2D surface



TAOS Model Includes Additional Effects from Test Phenomena

- Actuator dynamics
  - Internal states are tracked for actuator performance (heritage method)
- Actuator attach Kinematics
  - Actuator moment arm and direction change as a result of the engine deflection
- Actuator coupling effects
  - One actuator can induce movement in the other actuator DoF
- Controller Effects
  - Gain scale factor nonlinearity
  - Quantization



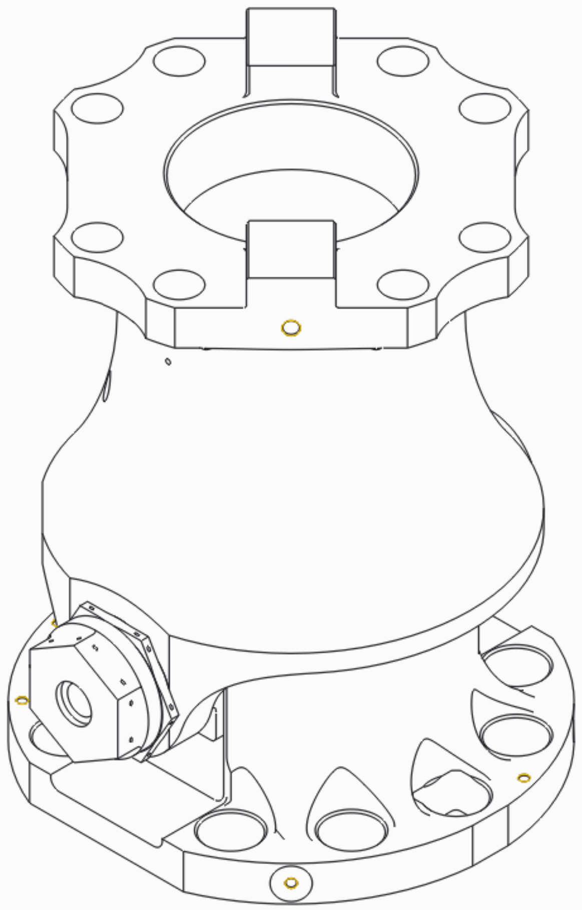


Actuator Deflection with Engine Rotation

Modeling Gimbal Joint Friction

- Different Models
  - Coulomb
  - Dahl
  - LuGre
  - Modified LuGre

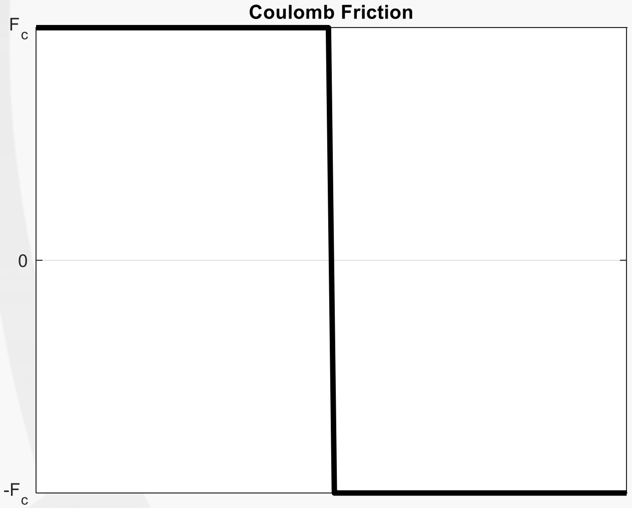
- 2D gimbal Surface implementation
  - SSME gimbal joint is a true spherical bearing under thrusting conditions
  - More accurate representation of friction versus 2 single DoF models
  - Project friction into direction opposite to the velocity (simple case)



RS25 Gimbal Assembly

Coulomb Friction

- Coulomb friction is a simple approach to friction modeling that operates via the following logic:
  - If there is nonzero velocity, then there is a friction force in the opposite direction to the velocity
  - This force will match the external forces until the external forces exceed the maximum coulomb force
  - Coulomb force stays at maximum value until the external force reaches the coulomb force

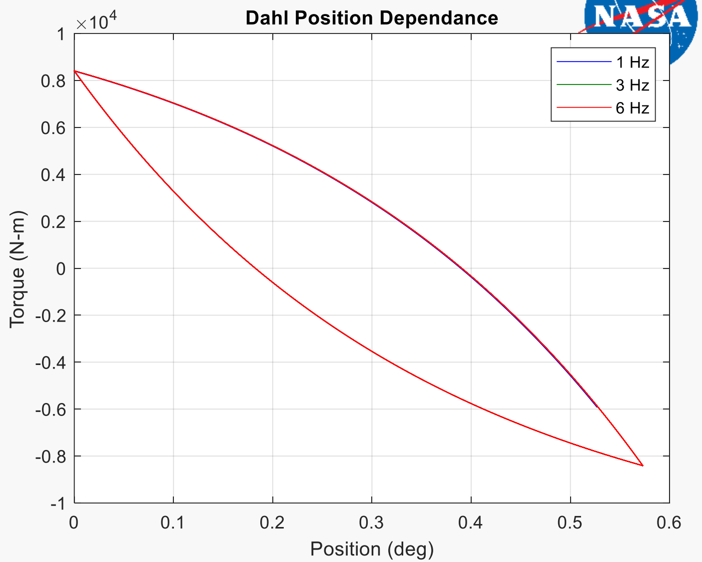


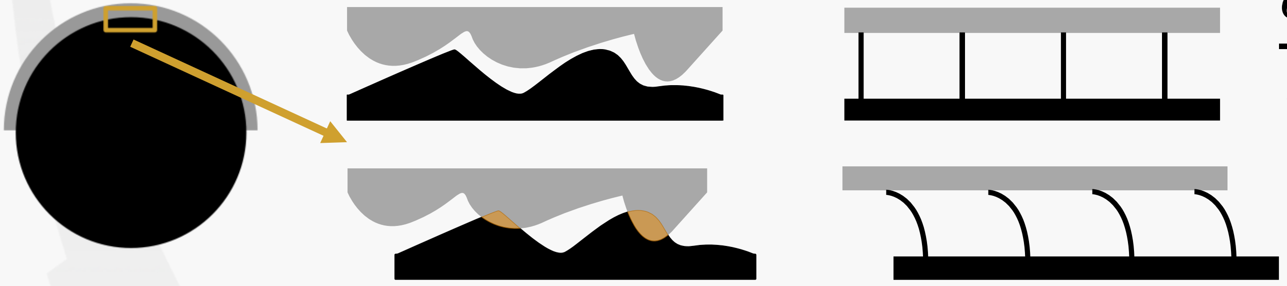
$$\begin{cases} \vec{F}_f = \vec{F}_e & , \quad \vec{F}_f \leq \vec{F}_e \\ \vec{F}_f = \mu_f N \dfrac{\vec{v}}{\|\vec{v}\|} & , \quad \vec{F}_f > \vec{F}_e \end{cases}$$

Equations from reference [2]

Dahl Friction

- Model developed by Philip Dahl of Aerospace Corporation for ball bearings in 1970s
  - Modeled to match behavior of stress-strain curve
- Assumes disparities in material can be modeled as "bristles"
  - The "bristles" act as springs and deflect as engine moves
  - Stiffness value is used to relate deflection to force
  - Position dependent friction model





Direction of gimbal motion

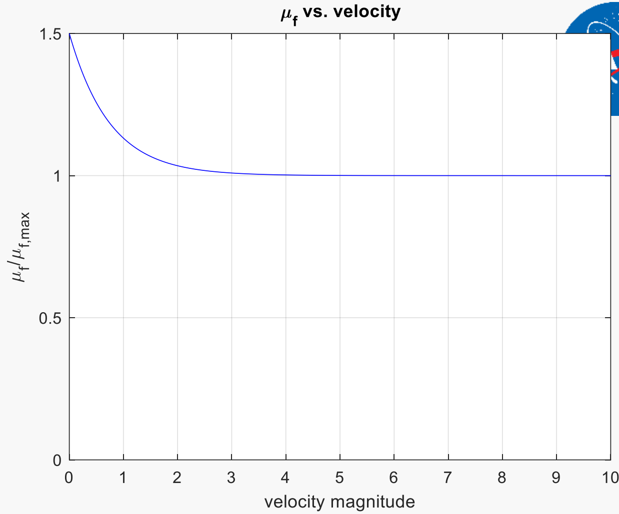
$$\frac{d\vec{z}}{dt} = \|\vec{v}\|(\hat{v} - \frac{\vec{F}_f}{F_c})^{\alpha}$$

$$\vec{F}_f = \sigma_0 \vec{z}$$

Equations from reference [4]

LuGre Friction

- LuGre friction is very similar to Dahl except it has three extra features:
  - Damping terms for the bristle velocity
  - Viscous term for the gimbal surface velocity
  - Velocity dependent Stribeck effect
    - Friction coefficient is higher at lower velocity
    - Meant to incorporate the stiction phenomenon
      - Deflection of disparities causes local increases in stiffness due to plastic deformation of material



Bristle Stiffness

Viscous Damping

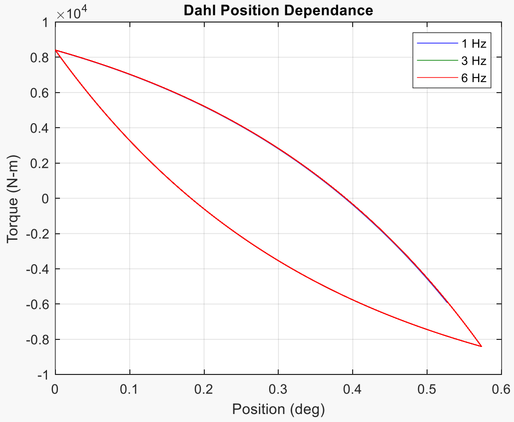
$$\vec{F}_f = \sigma_0 \vec{z} + \sigma_1 \frac{d\vec{z}}{dt} + \sigma_2 \vec{v}$$

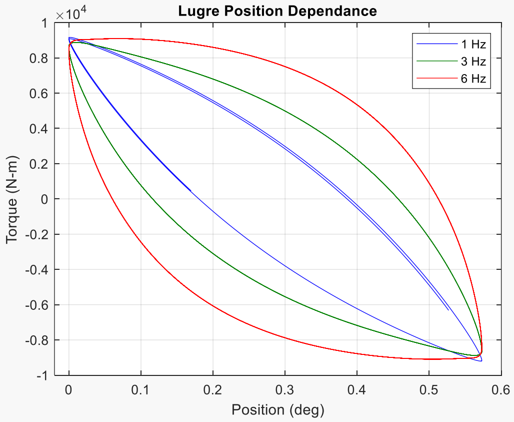
Bristle Damping

Stribeck Effect:

$$F_s = F_c \left(1 + (\gamma - 1)\, e^{-\left(\frac{\|\vec{v}\|}{v_s}\right)^2} \right)$$

$$\frac{d\vec{z}}{dt} = \|\vec{v}\| \left(\hat{v} - \frac{\vec{F}_f}{F_s}\right)$$





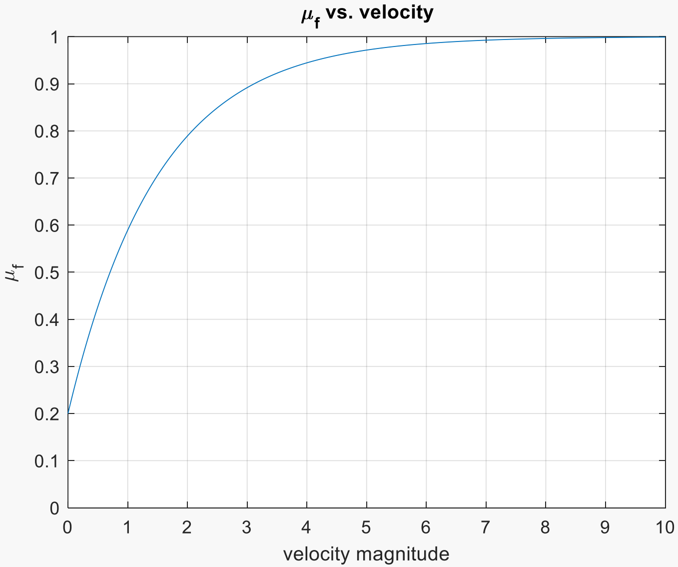
Equations from reference [2]

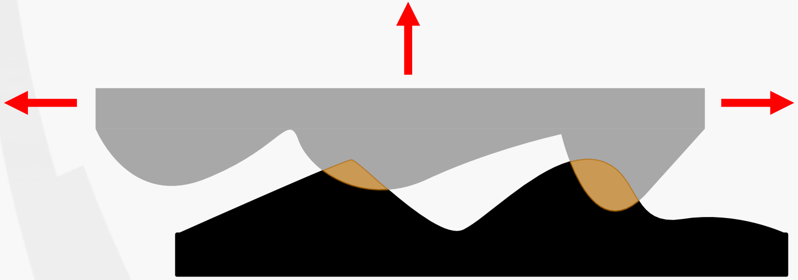
Modified LuGre

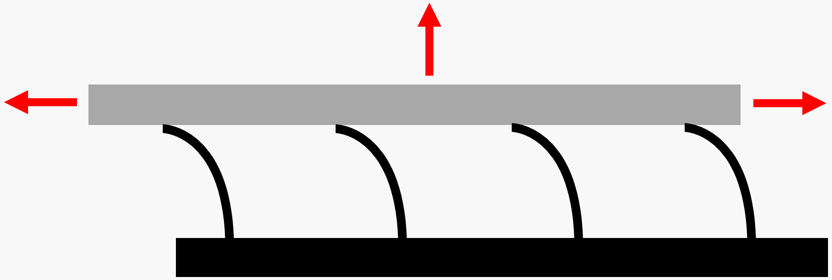
- LuGre modification introduces additional rate dependent term
  - Velocity dependent decrease in friction coefficient at low velocities

$$\mu_f = \mu_{f,0} e^{-\left(\frac{\|\vec{v}\|}{v_{vib}}\right)}$$

  - In and out of plane vibration movements can lead to decreased friction coefficient
  - Extends LuGre velocity dependence to also consider decline in friction seen in test data at lower velocities

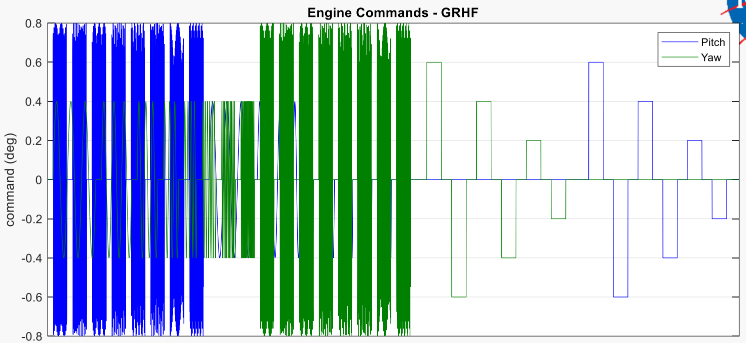


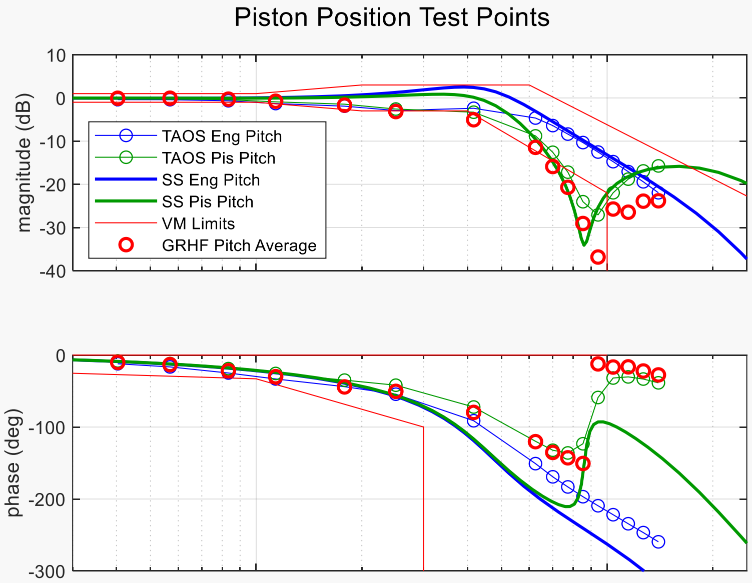




Using TAOS to Model GRHF Test Data

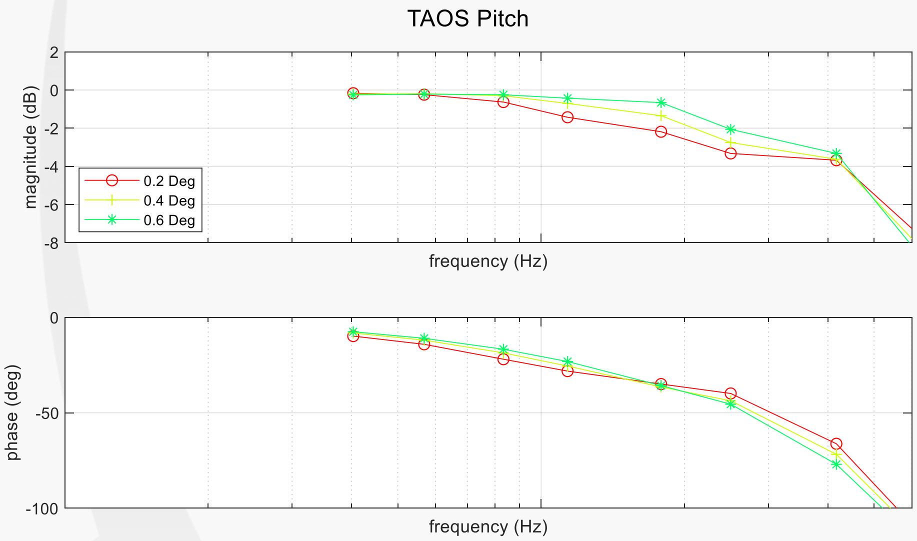
- The as-tested TVC response was simulated using TAOS
  - Match load resonance location (notch)
  - Gain degradation at mid test frequencies
  - Amplitude dependent frequency response informed by Shuttle MPTA testing
  - Proper step response characteristics
- TAOS friction parameters were explored to best match test
- Frequency analysis was completed using describing function reconstruction at the sine frequencies seen in test
- Data was compared to measured current, piston position and string pot data
- Modified LuGre produces the best test behavior in all metrics
  - Detailed matching of load resonance frequency subject of ongoing work

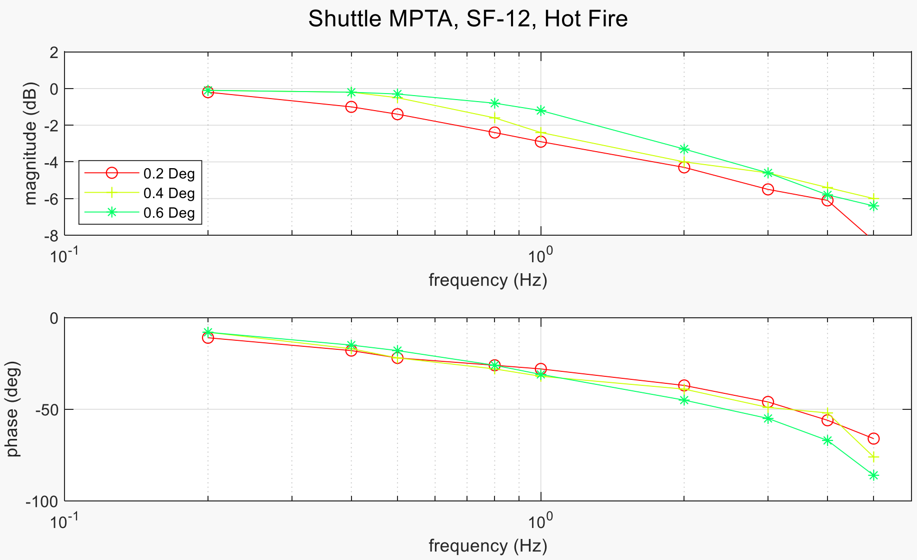




Matching GRHF Behavior – Amplitude dependance

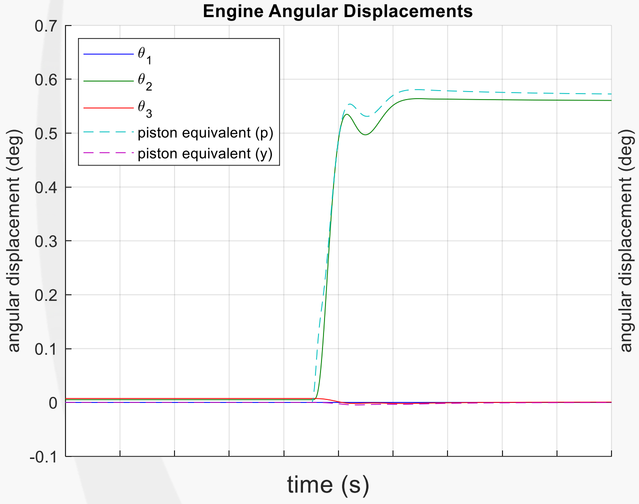
- Amplitude dependent behavior was seen in Shuttle MPTA frequency response, so it was desired for the GRHF model fit
  - Adjustment made so that approximate gain drop seen from 0.6 deg to 0.2 deg was present
- Amplitude dependence gain and phase dependance can lead to vehicle flight control limit cycling

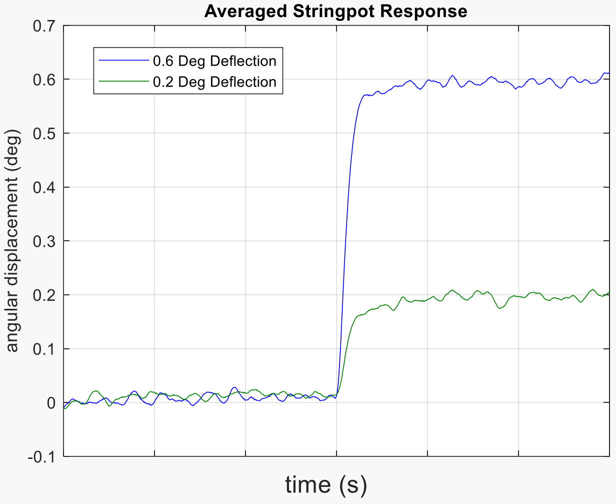


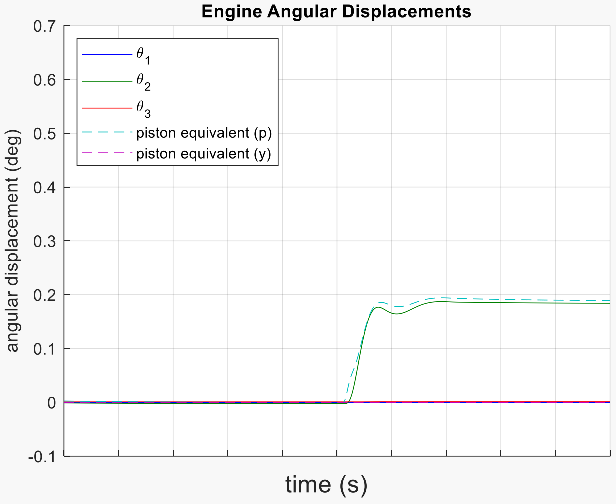


Matching GRHF Behavior – Step Response

- GRHF Step Response
  - Slight offset from commanded value
  - Return to zero behavior present with little offset
  - Rise time longer for smaller commands
  - Slightly longer response for return commands
- TAOS rate dependent friction terms used to mimic behavior seen in test for steps







Summary and Insights

- Demonstrated high fidelity modeling of coupled DoF with a custom tool
  - Additional fidelity over the heritage planar approach:
    - Effect of engine movement on actuator torque
    - Improved test correlation via advanced friction modeling
    - Coupled axis effects and kinematic effects
- Friction can have large effect on TVC response
  - Major effects:
    - Decrease in gain and phase response
    - Amplitude dependent behavior (depending on model)
    - Large change to step response characteristics
  - When looking at odd TVC phenomena, friction is a good place to start
- Future work
  - Friction model approximations for linear system analysis
  - Effects of friction torque on soft thrust structure
  - More vehicles and engines tested in TAOS

Backup: References

1. Barrows, T. M., & Orr, J. S. (2021). Dynamics and simulation of flexible rockets. Academic Press.
2. Olsson, H., Åström, K. J., Canudas de Wit, C., Gäfvert, M., Lischinsky, P. (1998). Friction models and friction compensation. European Journal of Control, 4(3), 176–195. https://doi.org/10.1016/s0947-3580(98)70113-x
3. Astrom, K. J., & Canudas-de-Wit, C. (2008). Revisiting the Lugre friction model. IEEE Control Systems, 28(6), 101–114. https://doi.org/10.1109/mcs.2008.929425
4. Dahl, P. R. (1968). A Solid Friction Model. https://doi.org/10.21236/ada041920

Backup: Modeling Engine Motion with Boltzmann-Hamel Equations

- Using the Boltzmann-Hamel EoM we start with the following equations:
  - Used because reference center of integration is gimbal and not CG
  - This allows us to constrain DoF without requiring Lagrange multipliers
  - Kinematic equations are approximated as second order Taylor expansions

$$\frac{d}{dt}\frac{\partial T}{\partial \vec{v}} + \vec{\omega}^{\times}\frac{\partial T}{\partial \vec{v}} = \bar{f} \qquad \frac{d}{dt}\frac{\partial T}{\partial \vec{\omega}} + \vec{\omega}^{\times}\frac{\partial T}{\partial \vec{\omega}} + \vec{v}^{\times}\frac{\partial T}{\partial \vec{v}} = \vec{g}$$

- This calculation can be simplified into a matrix computation using a mass matrix (*M*), generalized force Vector (*Q*), and a momenta vector (*R*)

$$\vec{c} = m_E r \vec{C}_G \qquad \mathbf{Q} = \begin{bmatrix} \vec{f}_b \\ \vec{\tau}_b \end{bmatrix}$$

$$\mathbf{M} = \begin{bmatrix} m_E \mathbf{I} & -\vec{c}^{\times} \\ \vec{c}^{\times} & \mathbf{J}_n \end{bmatrix} \qquad \mathbf{R} = \begin{bmatrix} \vec{\omega}^{\times}\vec{\omega}^{\times}\vec{c} \\ \vec{\omega}^{\times}\mathbf{J}_n\vec{\omega} \end{bmatrix}$$

$$\begin{bmatrix} \ddot{x}_{b,1} \\ \ddot{x}_{b,2} \\ \ddot{x}_{b,3} \\ \dot{\omega}_1 \\ \dot{\omega}_2 \\ \dot{\omega}_3 \end{bmatrix} = \mathbf{M}^{-1}(\mathbf{Q} - \mathbf{R})$$

Equations from reference [1]